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# Breccia Pipes—Products of Exsolved Vapor from Magmas

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## Abstract

A fundamental question any proposed model of breccia pipe formation must answer is how the void, necessary to accommodate the breccia, was created. Once a void of sufficient size is produced, the major aspects of breccia pipes (fragment character and distribution, sheet fracture boundaries, and dimensions) follow naturally and in analogy to the collapse of underground workings.

We propose that the prebreccia void was formed by magmatic water which exsolved as the pluton rose to shallower depths and lower pressures and was trapped for a time beneath the cooled rind in the apical region of the pluton. Eventual piercement of the rind by this hydrous bubble would lead to: 1) a drop in $P_{H_2O}$ in the bubble, 2) pinching of the lower portion of the vapor void by viscous magma, 3) crystallization of magma as $P_{H_2O}$ drops, 4) buckling of void walls and onset of stope caving, 5) continued stope cave filling of void, and 6) invasion of the breccia pipe by ground water not in chemical equilibrium with fragments. Mass balance calculations indicate the proposed void-generating mechanism is feasible for the Santa Rita, New Mexico, porphyry system. The porphyry stock mass, $1.6 \times 10^{13}$ kg, could have exsolved $9.6 \times 10^{11}$ kg of $_{H_2O}$ during its cooling history. At 800°C and 0.5 kb, $V_{H_2O} = 8.7 \times 10^9$ m$^3$, the exsolved water volume is more than adequate to account for the prebreccia void volume, $V_{void} \approx 5.5 \times 10^7$ m$^3$, of the two pipes associated with the Santa Rita stock.

## Introduction

A FUNDAMENTAL question any proposed model for breccia pipe formation must answer is how the void, necessary to accommodate the breccia pipe, was created. Once a void of sufficient size is produced, the major aspects of breccia pipes (the block distribution, sheet fracturing, etc.) would follow naturally and in analogy to the collapse of underground workings and the stope mining method. A more modern analogy to collapse would be the breccia chimney formed by detonation of a nuclear device. Sheet fracturing parallel to the walls and top would be expected. Mixing and block rotation would be expected to be greatest in the lower portions of the pipe. The pipe would cease to grow upward when the original void was filled with breccia. An upward gradation into horizontal and vertical sheet faulting could be expected.

Sillitoe and Sawkins (1971) recognized the fundamental question and proposed that the necessary void be created by dissolution of the hot rising fluids. They recognized that their explanation did not represent a unique model but felt the field evidence for fluid corrosion was compelling.

The interaction of hydrothermal fluids with the breccia material (corrosion) that is observed could be, and in fact appears to be, a postpipe phenomenon. In any case, for Sillitoe and Sawkins' hypothesis to become operative, large quantities of every reactive solvent would be required. It is somewhat difficult to imagine how a solvent out of equilibrium with the rocks through which it was flowing could be locally, selectively applied to just the area of the breccia pipe.

The present authors suggest an alternate explanation: that the void necessary for formation of breccia pipes is generated by the exsolution of water from the magma during pluton emplacement. The magmatic water is trapped for a time beneath the cool outer skin of the plutonic mass. In this paper we show 1) that the volume of water available in a water-rich pluton is more than sufficient to provide the volume necessary to account for the observed breccia pipes; 2) that a cool rim will form rapidly on a rising pluton, and that this rind is sufficiently thick to account for the depth extent observed for most breccia pipes, i.e., 100–200 meters; we argue 3) that an exsolved fluid bubble will be trapped for a time beneath this cool rind, but that the bubble will eventually break through, and 4) that such a mechanism could produce breccia pipes that feather into sheet fractures in their upper portions and pinch out in their lower portions.

A model is developed specifically from breccia pipes in central Chile discussed by Sillitoe and Sawkins (1971) and the Whim Hill breccia at Santa Rita, New Mexico, discussed by Kerr et al. (1950).

## Observational Facts

The Whim Hill breccia is an elongate body in plan, 500 meters long, 100 meters wide, and 200 meters in vertical extent (Fig. 1). The estimated total volume of this breccia is $10^7$ $m^3$. Assuming a rock will double its volume due to brecciation, the initial void space associated with the uncemented breccia is $0.5 \times 10^7$ $m^3$. The breccia is situated in the apical region of the stock.

The Whim Hill breccia contains angular fragments of Santa Rita stock ranging in size from one-millimeter grains to blocks 30 centimeters across. The majority of the Whim Hill pipe is composed of larger (6–10 cm) blocks locally cemented by pyrite or magnetite, but smaller fragments commonly fill the interstices. The pipe boundaries are characterized by sheet fracturing that gradually changes outward to blocky fracture sets, the latter being typical of the entire stock (Schaffner, 1971).

The breccia pipes in northern and central Chile discussed by Sillitoe and Sawkins (1971) are somewhat smaller than the Whim Hill, but display important features that are relevant to the origin of breccia pipes in plutonic rocks. The Chilean pipes are almost all confined within granodiorite "batholiths." They are mineralized with tourmaline, sulfide, sulfate, carbonate, and quartz crystals which contain NaCl-rich fluid inclusions. The typical plan views and cross sections are shown in Figures 2 and 3. Various levels of erosion of these pipes are recognized. The apexes of breccia pipes are characterized by decreasing numbers of breccia fragments and in-

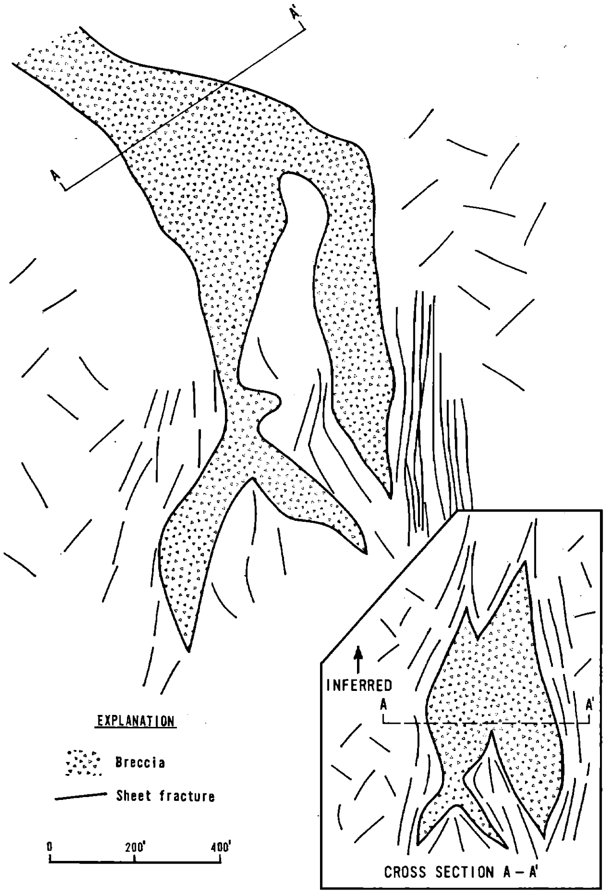


FIG. 1. Plan map, Whim Hill breccia, Santa Rita, New Mexico, generalized from Geology Department map (Schaffner, 1971).

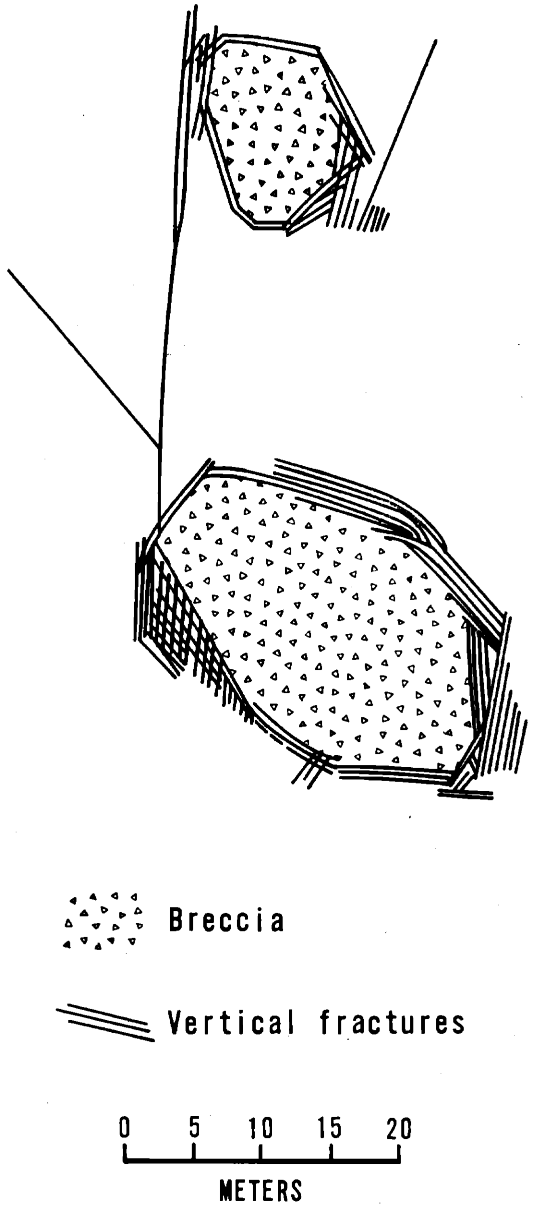


FIG. 2. Plan of two small breccia pipes in the Cabeza de Vaca group emphasizing the nature of typical sheeted contacts. (Originally published as fig. 3 in Sillitoe and Sawkins, 1971.)

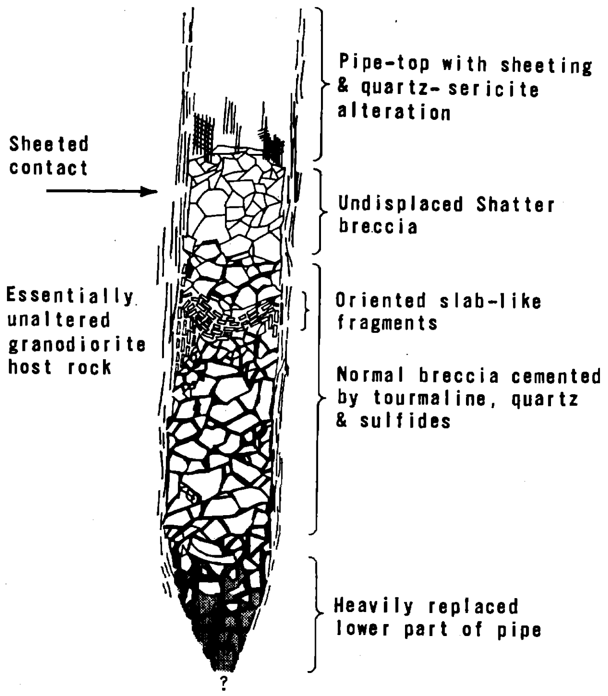


FIG. 3. Interpretive cross section of a typical Chilean breccia pipe, illustrating our conception of the vertical changes which might be encountered within a pipe. (Originally published as fig. 11 in Sillitoe and Sawkins, 1971.)

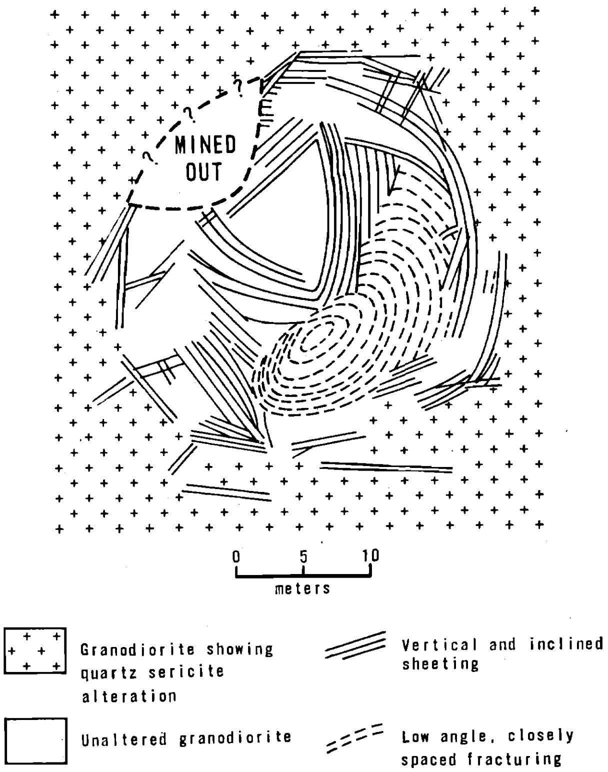
crease in sheet fracturing. The plan view of the San Pedro C pipe is typical of the uppermost expression of these pipes (Fig. 4). The interpretive cross section in Figure 3 is particularly relevant in reconstructing the stress fields responsible for the breccia pipe and in determining the level of erosion in other pipes. It should be noted that breccia pipes appear to fade upward into sheet fracturing. Thus the amount and sizes of rock material that could have been ejected upward out of the pipe would appear to be limited. From the calculated volume of the void one can assume that essentially no material was ejected upward. Sillitoe and Sawkins found no direct evidence of downward termination of the pipes they observed. They refer to other sources which depict downward termination and remain open on the question. The Whim Hill pipe appears to be terminated downward, however.

In summary, the Whim Hill and Chilean pipes discussed above are characterized by:

1. Dimensions and shape: Elongate, vertical axis with a height to minor width ratio > 3:1. The Whim Hill pipe is elongate in plan with the horizontal axes ⟫ the vertical axis, whereas the Chilean pipes are roughly circular in plan (Fig. 1).

2. Fracturing: Sheet fracturing parallel to the pipe walls and over the top of the pipe (in the Chilean case) (Figs. 3, 4a, and 4b). At least some pipes terminate upward into sheet faulting (Fig. 4a).

3. Fragmentation: Angular with only minor "rock flour" bounded by sheet fractures and grading up-



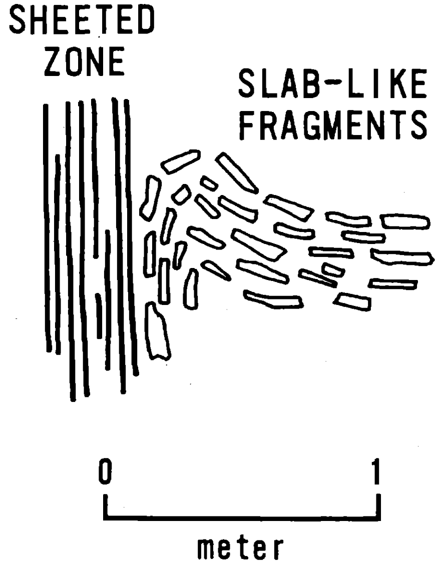


FIG. 4a. Plan of the San Pedro C pipe-top, San Pedro de Cachiyuyo district, showing undisplaced vertical sheeting, and inclined fracturing in the northeast part of the structure. (Modified from fig. 7 of Sillitoe and Sawkins, 1971.)

FIG. 4b. Sketch of the configuration of slablike fragments adjacent to pipe contacts. (Originally published as fig. 6 of Sillitoe and Sawkins, 1971.)

ward into fractured blocks that have been only slightly displaced.

4. Host: Generally block-fractured granodiorite stocks.

The breccia pipes discussed here do not show evidence of being formed by tectonic events such as faulting. Fault intersections, shearing, and displacement of rock units are lacking. The hypothesis that a large vapor bubble generated the prebreccia void seems most consistent with the observed field facts and theories of plutonism.

## Breccia Pipe Process

### *Breccia void volume compared to volume of exsolved magmatic water*

There is in general more than enough water in a water-rich magma to provide the fluid volume necessary to form the observed breccia pipes. For example, as estimated previously the volume of the liquid/vapor void of the Whim Hill breccia is about $0.5 \times 10^7$ m$^3$. The maximum $H_2O$ content of a granodiorite magma is about 6 wt %, most of which is exsolved ("boiled off") between 10 km and 3 km (Burnham, 1967). The Santa Rita stock is about 2,400 × 1,500 meters in plan and extends to 1,500 meters(?). Therefore, the magma volume was at least $5.4 \times 10^9$ m$^3$ or a mass of $1.6 \times 10^{13}$ kg.

$M$ stock $= 1.6 \times 10^{13}$ kg
at 6 wt % $H_2O$
$M_{H_2O} = 9.6 \times 10^{11}$ kg
$V_{H_2O}$ at 800°C and 0.5 kb $= 9.1$ cm$^3$/gm
$V_{H_2O} = 8.7 \times 10^{12}$ liters $8.7 \times 10^{15}$ cm$^3$ $=$ $8.7 \times 10^9$ m$^3$
$\therefore V_{H_2O}$ predicted $= 8.7 \times 10^9$ m$^3$.

The volumes of the Lovers Lane breccia, also associated with the Santa Rita system, is somewhat larger than the Whim Hill pipe. The void volume of the Lovers Lane breccia pipe, for example, can be estimated to be $5 \times 10^7$ m$^3$. The Lovers Lane breccia is found predominantly in the sedimentary host rocks for the stock and, if propagated from the underlying stock, a corresponding volume of breccia is expected within the stock. In summary for the Santa Rita system:

| *Prefragmentation Void Estimate* | *Water Void Volume Predicted* |
|---|---|
| $V_{\text{Whim Hill}} = 5 \times 10^6$ m$^3$ | |
| $V_{\text{Lovers Lane}} \approx 5 \times 10^7$ m$^3$ | |
| $V_{\text{void}} = 5.5 \times 10^7$ m$^3$ total | $V_{H_2O} = 8.7 \times 10^9$ m$^3$ |

Other breccia pipes similar to the Whim Hill may have been present but are now mined away (W. W. Baltosser, pers. commun., 1972).

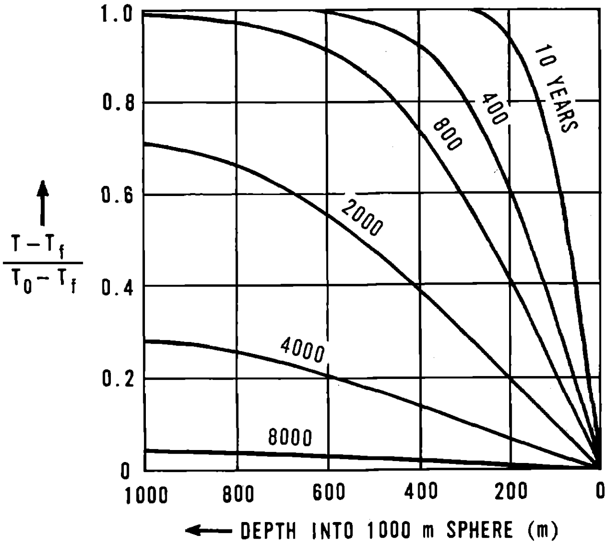


FIG. 5. The cooling history of a granite sphere initially at some uniform temperature $T_0$ whose surface is suddenly put at $T_f$°C. (Adapted from fig. 29, p. 234 of Carslaw and Jaeger, 1959.) Curves are for various values of $kt/a^2$ which may be converted to years if $a$ = radius of the granite sphere = 1,000 m, $k$ = thermal diffusivity of granite = $1.6 \times 10^{-2}$ cm$^2$/sec. Notice that a cold rind is very quickly formed on the pluton. We assume a specific heat, $c_p$, of 0.2 cal/gr°C (Kaye and Laby, p. 60), thermal conductivity, K, of $10^{-3}$ cal cm/sec°C, and a density, $\rho$, of 2.65 gr/cc for granite. The thermal diffusivity $k = K/\rho c_p = 1.6 \times 10^{-2}$ cm$^2$/sec.

### *Cooling history of a rising magma*

The cooling history of a rising magma having dimensions of a plutonic mass, such as the Santa Rita stock, can be approximated by reference to Figure 5. Consider a sphere of 1,000 meters radius initially at some temperature, $T_0$. Assume that when the pluton encountered water-rich host rocks, the surface of the pluton was suddenly set at some different, cooler, temperature, $T_f$. As indicated by the relation between temperature, depth into sphere and time (Fig. 5), a cold rim a few meters thick will form in a few years. This cool rim of the magma represents a solid shell if the temperature drop occurs across the solidus of the lowest melting temperature fraction of the system. The solid rind thus generated may initially be relatively impermeable to water exsolving from the contained magmatic liquid. The trapped vapor bubble we envision is shown in Figure 6a.

At this point we have made two critical assumptions that warrant some discussion: 1) that the vapor bubble will be trapped for a time (until it reaches some critical size) beneath the cool rind of the pluton, and 2) that water exsolves from and migrates to the upper portion of the pluton. In the first case we must assume the rind to be quite impermeable. It must be unfractured. On cooling, tensional cracks would tend to form as a result of thermal contraction.

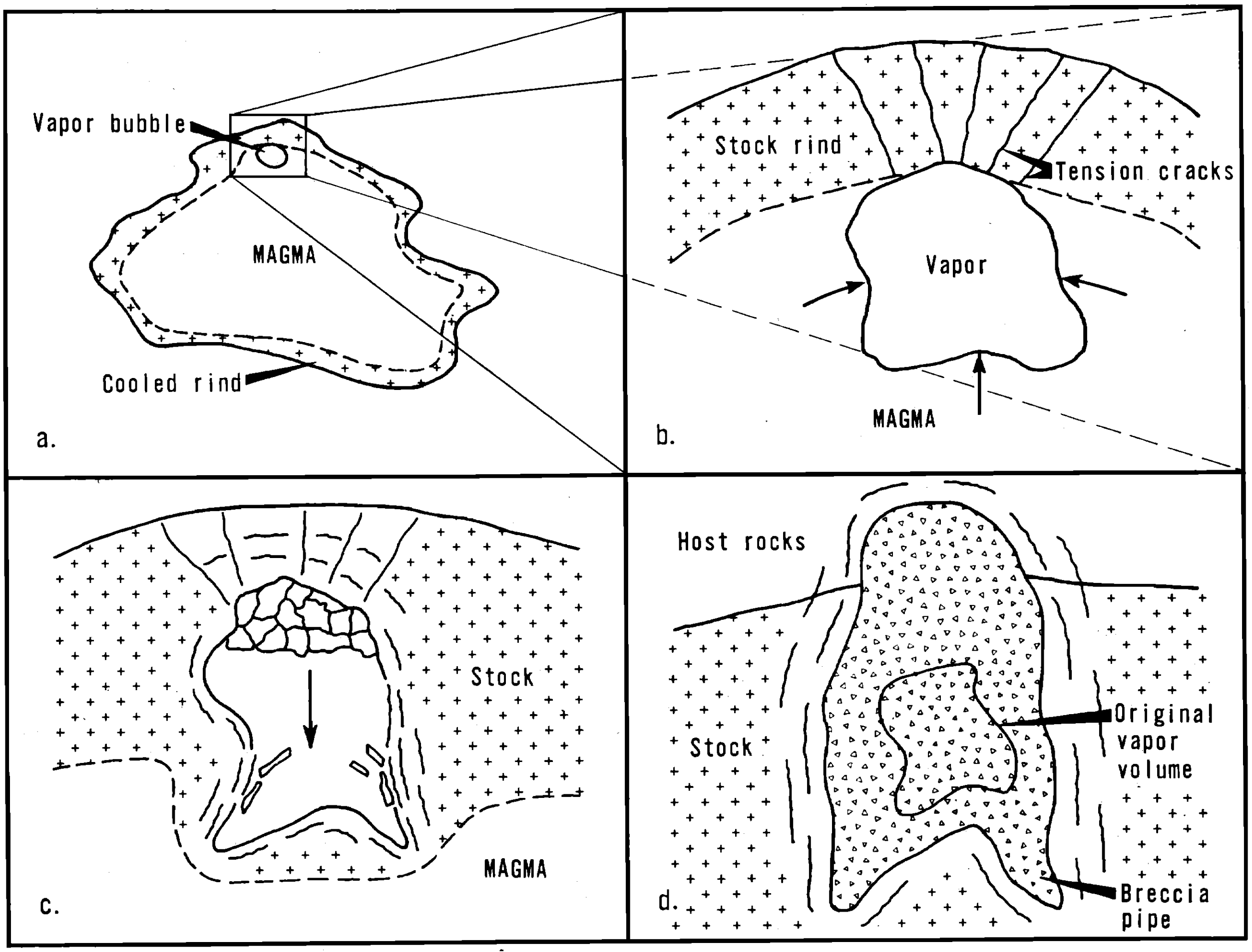


FIG. 6. (a) Magmatic water exsolves from rising pluton as a result of decreasing solubility in melt, but is trapped beneath cool outer rind of pluton. (b) The bubble eventually becomes large enough and the rind brittle enough for bubble to break through. (c) The resulting drop in hydrostatic pressure signals collapse of the cavity by sheet fracturing and blocky stope caving. (d) The pipe continues to grow until void is filled and thus supported by breccia. The pipe may grow upward above the original pluton margins depending on caving properties of stock versus host rocks.

It seems likely, however, that these would be filled initially and plugged as they are formed by liquid magmatic phases from the still hot pluton. Hence, it may not be unreasonable to assume an impermeable rind. Later this should not be the case, and further cracking of the cool rind might ultimately make it quite permeable.

The migration of exsolved water upward and coalescence into a liquid vapor void assume that the inner portions of the pluton is a partial melt while water is exsolving. This appears reasonable and consistent with pluton emplacement mechanisms. The hydrous phase migration to the upper part of the pluton occurs in response to the density contrast between two immiscible fluids. Note that in this model this exsolved vapor phase is in equilibrium with the pluton and therefore is *not capable* of chemical corrosion.

### *Piercement of the hydrous bubble through the plutonic rind*

The conditions under which a less dense vapor bubble at the bottom of a more dense elastic plate will pierce the plate and migrate to its upper surface have been discussed by Weertman (1971a, 1971b). He shows that piercement becomes possible when $(T - P + P') > 0$, where P is the hydrostatic pressure at the bottom of the elastic plate, P′ is the hydrostatic pressure at the top of the vapor bubble, and T is any horizontal tension that may exist in the plate (tension taken as positive, pressure also positive). Weertman states that it is unlikely that P′ will exceed P and thus feels at least some tension in the plate is required for piercement. Because of buoyant forces it seems clear that P′ should increase as the size of the liquid bubble increases. Also the stress

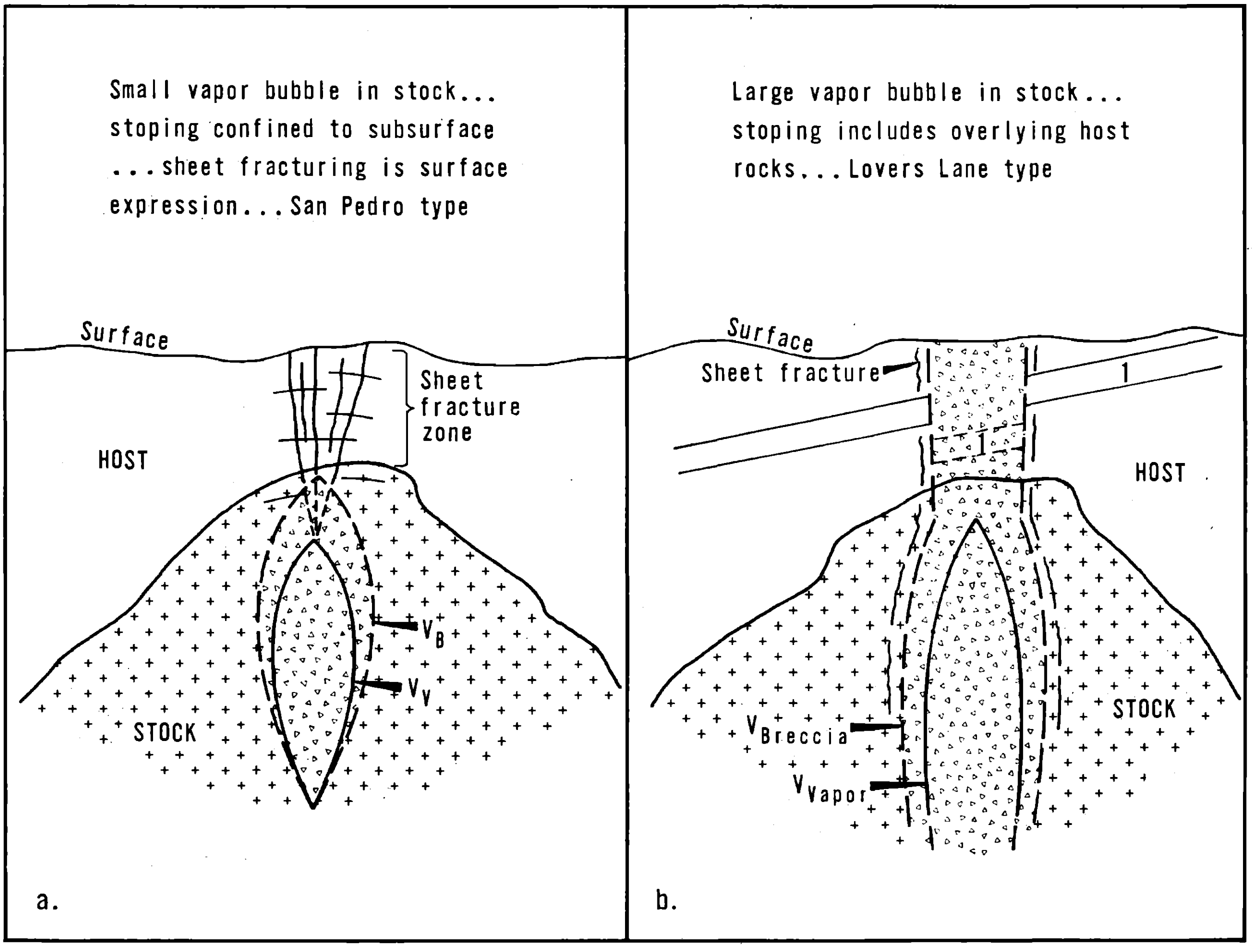


FIG. 7. Hypothetical cross section of breccia pipe geometries as function of vapor bubble volume.

distribution in our elastic plate is not hydrostatic; a choice of a hydrostatic pressure in the plate would be suspect. In particular, for an elastic solid in a gravity field, the horizontal confining stress is one third the vertical (if Poisson's ratio is 0.25). Thus $P < P'$ and we may require no tension in the plate for piercement.

In any case there is likely to be some tension in the plutonic rind produced from three sources: 1) further cooling and thermal contraction of the rind, 2) friction between the rind and the intruded sediments if the pluton is still rising, and 3) regional tectonic stresses. Thus, at least after the vapor bubble has reached some critical size, the bubble should pierce through the plutonic rind.

### *Formation of the breccia pipe*

The vapor release from the bubble along tensional cracks in the pluton rind results in 1) a drop of $P_{H_2O}$ in the bubble, 2) pinching of the vapor void by liquid magma in the pluton interior (Fig. 6b), 3) solidification of the confining magma due to $P_{H_2O}$ drop, 4) buckling of the void walls and the onset of stope caving as a result of the drop in fluid (supporting) pressure (Fig. 6c), 5) continued stope caving until void is filled (Fig. 6d), 6) the invasion of the breccia pipe by ground water not in chemical equilibrium with the pipe rock fragments.

The breccia pipe thus formed has high permeability relative to other formations in the hydrothermal system. Initially the pipe will be filled in places with water and in places with vapor. Thus the initial alteration-mineralization pattern in breccia pipes might be predicted to be erratic, and so observed in the Whim Hill pipe (W. W. Baltosser, pers. commun., 1972). Later fluid flow through the pipe might produce an extended alteration zoning since the fluid in the pipe will retain its "reaction" capacity a greater distance from the stock (because of the greater porosity and permeability of the pipe).

The vertical extent of breccia pipes depends on the vapor bubble size and caving characteristics of the stock and overlying host rocks. Some characteristics of breccia pipe "tops" for different vapor bubble sizes are suggested in Figure 7.

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